

Reply to Interactive Comment made by Referee #3

Hydrol. Earth Syst. Sci. Discuss., 9, C6623–C6624, 2013

7 February 2013

Our reply is in italic

We thank the anonymous reviewer (Referee #3) for his/her critical remarks. Clearly, they will help to focus the paper more to avoid confusion.

There are several research articles published in recent years related to drought at global scale. Some of the articles published based on quantification of hydrological droughts. Based on these several articles, I believe in the technical contributions, however the results look to be not well validated. Even different articles talk about different results with large variation in their discussion. When we talk about global hydrological drought, there are so much uncertainties involved (for example: land use pattern and ground water depletion) and it is not easy way to quantify drought episodes when we incorporate human induced dynamics. Even at the catchment scale we see large difference in hydrological droughts simply by incorporating slope of the watersheds. The authors demonstrated a simple approach to quantify hydrological droughts for different climatic patterns. The manuscript can be improved further.

- *The authors agree that several articles have been published on large-scale drought (see literature review, p. 12148, lines 18-22, old manuscript). We will add a few very recent studies (Dai, 2012; Sheffield et al., 2012). However, only a few of these studies that aim to present results for all climates around the globe really address hydrological drought using runoff/river flow data and following the threshold concept introduced by Yevjevich (1967) and further elaborated by a series of authors (e.g. Hisdal et al., 2004; Fleig et al., 2006). The threshold method defines drought as an anomaly (i.e. a deviation from normal conditions). Most of the large-scale studies deal with meteorological drought (using SPI), soil water drought (using PDSI) or using runoff/ river flow directly rather than the anomalies. In this sense the paper is innovative, and results will differ from existing other global studies because hydrological drought, deviates from meteorological or soil water droughts because of drought propagation (i.e. pooling, lengthening, delaying, attenuation, e.g. Tallaksen et al., 2009; Van Loon & Van Lanen, 2012).*
- *The modeling framework has been validated against observations and compared with the outcome of more detailed hydrological modeling studies in European catchments with contrasting climate and physical catchment structure (see item 3 below).*
- *The authors agree that land use has an impact on hydrological processes (e.g. evapotranspiration, groundwater recharge). Through these processes, it also affects the magnitude of drought characteristics (e.g. drought duration, deficit volume). The authors performed a sensitivity analysis (p. 12165, lines 10-19) with another land use (perennial crops instead of permanent grassland). The higher potential evapotranspiration and soil depth found for the perennial crops affected recharge and discharge and even the DD-SDV probability fields. However, the probability fields for all major climates changed, which had as a net effect that the Similarity Indices did not substantially change (2-6%). This proves that the conclusions are rather robust. The purpose of the paper is to demonstrate that the physical catchment structure (e.g. groundwater system) has a similar effect on drought characteristics as climate and that another land use does not lead to another conclusion.*
- *We excluded groundwater depletion from our analysis, because it is associated with unsustainable water use by human activities (i.e. water scarcity conditions). On the contrary, drought is a natural phenomenon that is caused by natural climate variability. We would like to keep the two phenomena, water scarcity and drought, separated to avoid confusion and consistency in the results. In this paper we focus on drought. In other studies we try to deal with both phenomena at the same time (Van Loon and Van Lanen, 2013). This is also the reason that we left out other human induced dynamics. We changed the definition of drought to clarify this difference to the reader.*
- *The slope of watersheds can indeed affect hydrological processes (e.g. overland flow on slowly-permeable top soils, evapotranspiration due to sun exposure). We agree that these kind of details are not included in this basically 1-D conceptual hydrological model as this was not the purpose of the study. Rather we are exploring the role of soils and aquifers in different climates across the world with a model approach that is more common for these scales (e.g. Haddeland et al, 2011 and references herein).*

I have following suggestions for the authors:

1. For the controlled experiment, how the scenarios are chosen? Is it based on the certain existing conditions?

We distinguished nine different scenarios (we called these realizations), i.e. three soils and three different groundwater systems (Section 2.3.3). The soil physical data were derived from a database with existing, real world soils. We selected three different soils covering a wide range of soil moisture supply capacities. The

three selected groundwater systems reflect existing groundwater response conditions, from a flashy response, typically for areas where the groundwater system/aquifer has a low transmissivity and it is drained by streams/drains not far apart ($j=100$ day) up to conditions where the distance between streams is several kilometres and the groundwater system/aquifer has a high transmissivity ($j=1000$ day). Observed stream-aquifer responses have been studied to determine the j values. Peters (2003) summarizes these.

We have revised the text to make clear that the realizations are based on existing soils and groundwater systems. The revised sentences are: "The soil information was derived from a standard series of existing soils that predominantly differ in soil texture (Wösten et al., 2001a, b)." and "Comprehensive drainage studies are the basis for Equations (7 and 8) and associated j values (Kraijenhof van de Leur, 1962; Ritzema, 1994)." (Sect. 2.3.3).

2. The authors can highlight their result in comparison to other findings for global drought. For, example, whether there is an increasing or decreasing pattern in drought? This will be a good contribution by the authors and strengthen the manuscript.

Several large-scale studies on trends in drought have been published recently (e.g. on global soil water drought, Dai, 2012; Sheffield et al., 2012, continental hydrological drought, Stahl et al., 2010; 2012; Hannaford et al., 2013). The observed trends on these scales are hard to explain because these depend not only on changes in climate forcing, but also on how catchment characteristics modulate climate signals. This paper may provide a valuable contribution to these trend studies through providing knowledge on controls of drought generation, which enables to better understand following trend studies. Further, the model design has the potential to unravel effects of climate control versus physical catchment structure on reported trends in hydrological drought.

We have revised the text to mention the potential to perform such a comprehensive trend analysis in a follow-up study. The revised sentence is: "The simulated time series with the conceptual hydrological model provide potential to unravel effects of climate control versus physical catchment structure on reported trends in hydrological drought (e.g. Stahl et al., 2010; 2012; Hannaford et al., 2013).....". (Sect. 4.2).

3. There is no validation of the model output. Is there anyway to validate the results?

The effect of using a relatively simple model has been reported by Tijdeman et al. (2012). They explored model performance of simple model used in this study against observations and the outcome of more detailed hydrological modeling studies in four catchments with contrasting climate and physical catchment structure. This exercise showed that the simple model can reasonably well simulate the streamflow hydrograph, except for the peak flows. However, this study focussed on low flow (recession) situations, which in principle can be well simulated by a single linear reservoir model. The performance exercise also showed that absence of overland flow can be approached if the reservoir coefficient j of the reference situation is replaced by a lower value.

We have revised the text to refer to the performance study by Tijdeman et al. (2012). The revised sentence is: "Tijdeman et al. (2012) explored performance of the rather simple conceptual model adopted in this study against observations and the outcome of more detailed hydrological modeling studies using HBV in four catchments with contrasting climate and physical catchment structure. This exercise showed that the simple model can reasonably well simulate the streamflow hydrograph, except for the peak flows. However, this study focussed on low flow (recession) situations, which in principle can be well simulated by a single reservoir model. Use of one single reservoir to represent groundwater (Fig. 1), was overcome through the inclusion of realizations with quickly-responding groundwater system ($j=100$ day) that represent flashy flow conditions." (Sect. 4.3).

4. When the climate pattern differs, the precipitation and evaporation pattern will differ. These two variables act as major driver of drought without much human intervention. There can be a discussion how it changes across different climatic patterns and where there is likely of more drought events. This discussion will lead to further involvement of land use and groundwater components.

The authors agree with the reviewer that lower precipitation and higher evapotranspiration than normal are the principal drivers for the development of hydrological drought. In snow-affected climates temperature deviations from normal may be an important factor as well (Van Loon and Van Lanen, 2012). As mentioned above, the physical catchment structure (i.e. land use, groundwater system) changes the climate signal, a process that we call drought propagation (i.e. the conversion of a meteorological drought into a hydrological drought). Drought propagation, which also depends on the climate, is a comprehensive topic, but it is already relatively well covered in earlier and upcoming studies (e.g. Changnon, 1987; Peters et al., 2003; Tallaksen et al., 2009; Van Loon and Van Lanen, 2012; Van Loon et al., 2013).

We have revised the text to refer to the references on drought propagation. The revised sentence is: "The model outcome can also be used to support studies on drought propagation (i.e. the conversion of a meteorological drought into a hydrological drought, e.g. Changnon, 1987; Peters et al., 2003; Tallaksen et al., 2009; Van Loon and Van Lanen, 2012), which also depends on climate and physical catchment structure." (Sect. 4.2).

5. HBV model concepts might be useful for small to regional scales. Is there any limitations of using this concepts for large scale?

The most important limitation of using conceptual hydrological models based upon the HBV concept for investigations that aim to present results for all climates around the globe, like our study, is the impossibility of calibrating the model for each selected cell. That is the reason that we have defined nine possible realizations, incl. associated parameter sets, which are based upon real world conditions (see also item 1). Most large-scale hydrological models (e.g. Haddeland et al., 2011) use a conceptual framework, which is very similar to the HBV concept.

We will add a line that calibrating of the conceptual hydrological model is impossible for large-scale studies. The revised sentence is: "It is uncommon to calibrate hydrological models that are used to present results for all climates around the globe (e.g. Haddeland et al., 2011) because gridded databases with observed runoff are lacking. In this study, as an alternative, realizations of land use, soils and groundwater systems were introduced, which were based upon real world parameter settings". (Sect. 4.3).

6. When the streamflow is considered for hydrological drought analysis most of the times the peaks are not able to be captured properly or even near to them. This will affect in choosing the threshold level for identifying the actual drought events. How these limitations can be overcome?

We agree with the reviewer that peaks are not well simulated with the conceptual hydrological model that has been used in this study (see also item 3). However, this limitation affects the hydrograph and the threshold in a similar way. Droughts are anomalies and are determined by comparing the hydrograph (different for each year) with the variable threshold (long-term average) (Section 2.1.3). So, droughts are relative implying that the absolute flow is less important. Thus, partly underestimating the peaks will have limited impact on the differences between DD-SDV probability fields (aim of the paper).

We will add a line that says that the simple model does not simulate peaks well, but that this does not affect the differences between DD-SDV probability fields. The revised sentence is: "The SIs for realizations with the quickly-responding groundwater system, which generates more flashy hydrographs, illustrate that even under these conditions the responsiveness of the groundwater system is important relative to climate".. (Sect. 4.3).

7. Considering groundwater component might be challenge for quantifying hydrological droughts. The reason being large scale exploitation in many part of the world. Therefore this component will have a varying impact on streamflow. A small discussion can highlight this issue.

We agree with the reviewer that large-scale groundwater exploitation leads to reduced streamflow. However, we excluded large-scale groundwater exploitation from our analysis, because it is associated with unsustainable water use by human activities (i.e. water scarcity conditions). On the contrary, drought is a natural phenomenon that is caused by climate variability. We would like to keep the two phenomena, water scarcity and drought, separated to avoid any confusion about the relative importance of the physical catchment structure versus climate on drought rather than on drought plus water scarcity.

We added the term "natural" in the definition of hydrological drought to inform the reader that we do not consider any human-induced activities because drought is a natural phenomenon. The revised sentence is: "Hydrological drought refers to a prolonged period with below-normal water availability with natural causes in rivers and streams, and lakes, or groundwater bodies.". (Sect. 1).

There are other issues but the above concerns can be addressed by the authors before publication. The authors have done a good job, however it needs revision before final decision.

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